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CALIBRATION OF PYROELECTRIC RADIOMETERS FOR INFRARED FLARE MEASUREMENTS

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes a set of pyroelectric radiometers which have recently been set up, successfully checked out, and are now in use for infrared flare plume radiation measurements, ~~at NAVWPNSUPPCEN Crane~~. These radiometers meet the criteria of system linearity, fast rise time, complete commercial availability (no modification of electronics required, for example), ambient temperature operation, and reasonably flat spectral response from the visible to mid-infrared (~15μm). The instruments are presently being used (with

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on 15 micrometers

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20. (CONT'D) the addition of bandpass filters) in the 3.0-4.0, 3.0-5.0, and 4.3-5.0 micrometer regions.

Calibration procedures for these radiometers are described. The basis of the calibration procedure is an Electrically Calibrated Pyroelectric Radiometer (ECPR) which is traceable to the National Bureau of Standards. The ECPR is used only as a laboratory calibration device, and is a different instrument than the set of pyroelectric radiometers used for measurement of flare radiation.

The ECPR is used to calibrate a blackbody. The ECPR is fitted with the band filter identical to the filters to be used with each pyroelectric radiometer. The blackbody is then used to calibrate each pyroelectric radiometer. These measurements are plotted to obtain a voltage versus irradiance calibration curve for each band being used with the pyroelectric radiometer system.

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DEFINITIONS OF TERMS FREQUENTLY USED

Electrically Calibrated Pyroelectric Radiometer (ECPR). This radiometer will be used as a primary standard in this procedure. All optical measurements will be traceable to this instrument, which is electrically traceable to NBS.

Blackbody. This is a commercially available blackbody simulator with variable temperature. Since the emissivity is generally 0.99 or better, the blackbody simulator will be referred to as a blackbody.

Pyroelectric Radiometer. This is a commercially available radiometer consisting of a pyroelectric detector, preamp, chopper, and lock-in amplifier. The detector is spectrally flat in the region of interest.

Filters. These are placed in front of the pyroelectric radiometer to limit the spectral bandpass to the band being measured.

SYMBOLS

Irradiance. (E_{band}) Power per unit area incident upon a surface for the spectral band to be measured. These units are watts per square centimeter, $W \cdot cm^{-2}$. For the purpose of this procedure, E_{band} is defined as the irradiance in the band of interest as if the filter had 100% transmittance in that band (and 0% out of band). This term, while not a standard one, is used for convenience in calculations to be described.

Average Transmittance. ($\bar{\tau}$) This is the average transmittance of the filter in the spectral region under consideration.

Observed Irradiance. (E_{obs}) This is the irradiance as read on the ECPR. This quantity differs from E_{band} in that the true in-band filter transmittance is used. Accordingly,

$$E_{obs} \, \bar{\tau}^{-1} = E_{band}$$

Radiant Intensity. (I_{band}) Power per unit solid angle from a point source. The units are watts per steradian, $W \cdot sr^{-1}$.

Radiance. (L_{band}) Power per unit solid angle per unit area of source projected normal to the solid angle. The units are watts per steradian per square centimeter, $W \cdot sr^{-1} \cdot cm^{-2}$.

Area. (A) The aperture area of the blackbody in square centimeters, cm^2.

Distance. (R) Measurement, in centimeters (cm), between aperture of blackbody (or position of flare) and detector.

Reference 1 describes the new standard symbols that have been recently accepted for radiation measurement quantities. For convenience, the old and new symbols are listed below:

	OLD	NEW
IRRADIANCE	H	E
RADIANT INTENSITY	J	I
RADIANCE	N	L

1. EQUIPMENT

1.1 General. Test equipment used should be calibrated and/or certified by a secondary standards laboratory at established intervals (see Table 1) against certified standards which have known valid relationships to national standards.

1.2 Equipment List

1.2.1 Electrically Calibrated Pyroelectric Radiometer (ECPR), Model RS-3940, Laser Precision Corporation, Yorkville, New York.

1.2.2 Lock-in Amplifier Model 186A, Princeton Applied Research, Princeton, New Jersey.

1.2.3 Pyroelectric Radiometer, Model KT-4130/111, Laser Precision Corporation, Utica, New York. See Appendix A for a further description.

1.2.4 Lock-in amplifier, Model 5101, EG&G Princeton Applied Research, Princeton, New Jersey.

1.2.5 Filter, Valtec Corporation, Waltham, Massachusetts, 3.0-5.0μm half-power points.

1.2.6 Filter, Valtec Corporation, Waltham, Massachusetts, 3.0-4.0μm half-power points.

1.2.7 Filter, Valtec Corporation, Waltham, Massachusetts, 4.3-5.0μm half-power points.

1.2.8 Blackbody, Model 11-200T, Barnes Engineering Company, Stamford, Connecticut.

1.2.9 Precision Digital Voltmeter, Keithley - DVM Model 168 Auto-ranging, Keithley, Inc., Cleveland, Ohio.

1.2.10 Baffle (Based on those described on reference 2, page 266).

2. SYSTEM CALIBRATION PROCEDURE

2.1 General. The system used consists of an Electrically Calibrated Pyroelectric Radiometer (ECPR) (reference 3) which is used to calibrate a blackbody set at 1000 degrees Celsius (1273K). See Table 2 for specifications. The ECPR is used only as a laboratory calibration device and is a different instrument than the set of pyroelectric radiometers (described below) used for measurement of flare radiation. The ECPR detector is fitted with the band filter identical to the filters to be used with each pyroelectric radiometer. The blackbody is then used to calibrate each pyroelectric radiometer in the 3.0 to 5.0, 3.0 to 4.0 and 4.3 to 5.0 micrometer regions.

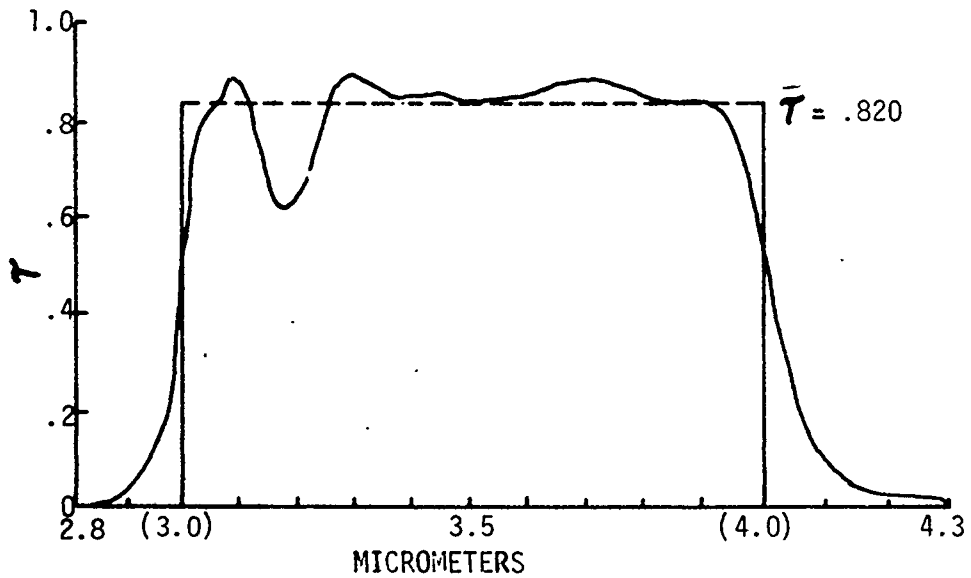
These measurements are plotted to obtain a voltage versus irradiance calibration curve for the particular bandpass being used with the pyroelectric radiometer system.

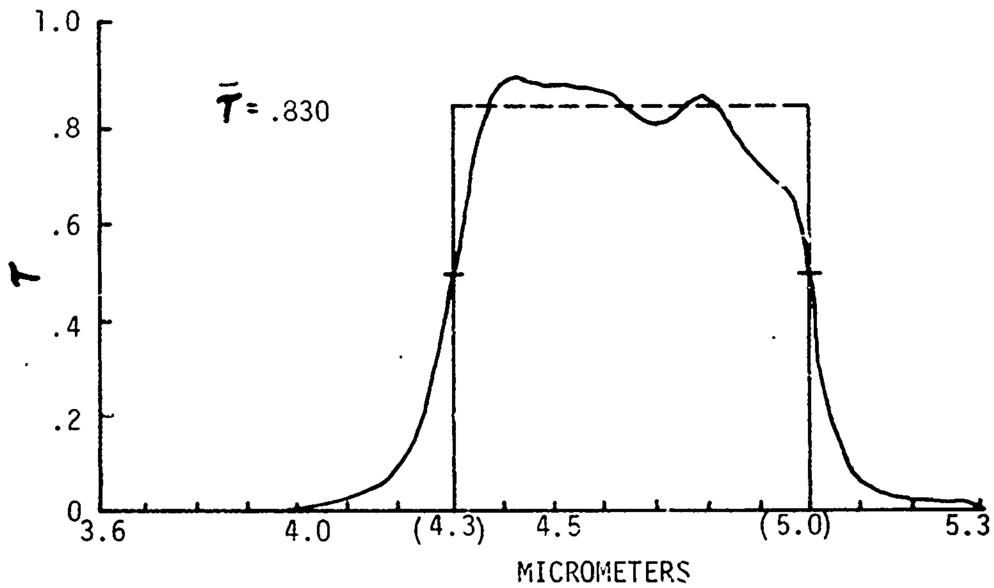
2.2 Calibration of Standards. Calibration of test equipment should be verified prior to each series of tests.

2.2.1 ECPR Calibration. Electrical calibration of the ECPR should be done in accordance with reference 4, Chapter 5, and reference 5 by a calibration laboratory against NBS traceable electrical standards.

2.2.2 Filter Transmittance. The 3.0 to 5.0, 3.0 to 4.0 and 4.3 to 5.0 micrometer band filters used with the ECPR and the pyroelectric radiometers should be measured for spectral transmittance with a spectrometer to determine the bandpass and to check for transmittance of radiation outside the desired region. Figure 1 indicates the in-band transmittance. Transmittance in the out-of-band regions, measured from .35 to 40 micrometers, was less than 0.001. Figure 2 shows the spectral response of the pyroelectric

FIGURE 1. FILTER TRANSMITTANCES





THE VALUES IN PARENTHESES ARE THE HALF-POWER WAVELENGTHS, WHILE THE $\bar{\tau}$'s ARE THE AVERAGE TRANSMITTANCES FOR RECTANGLES OF EQUAL AREA AS THE ACTUAL CURVE

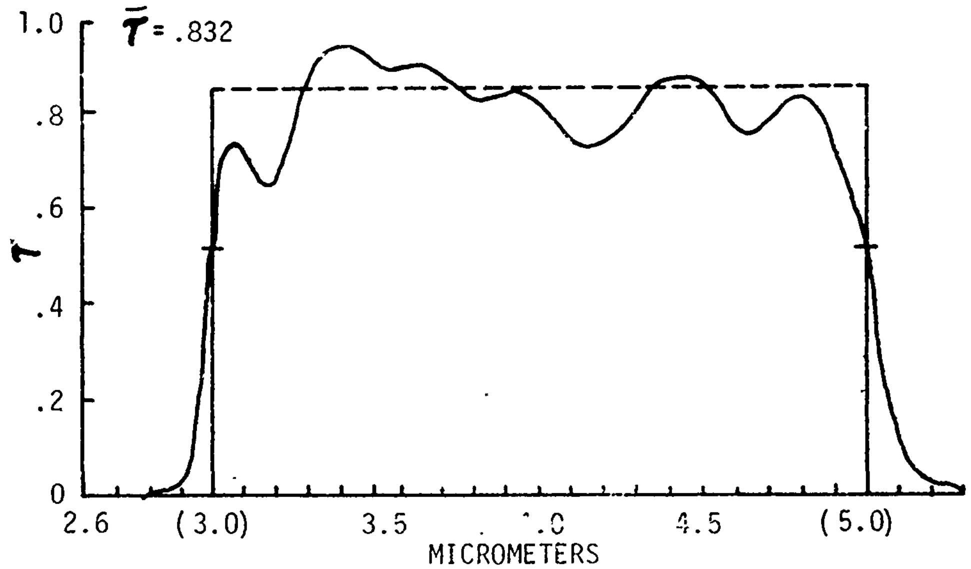
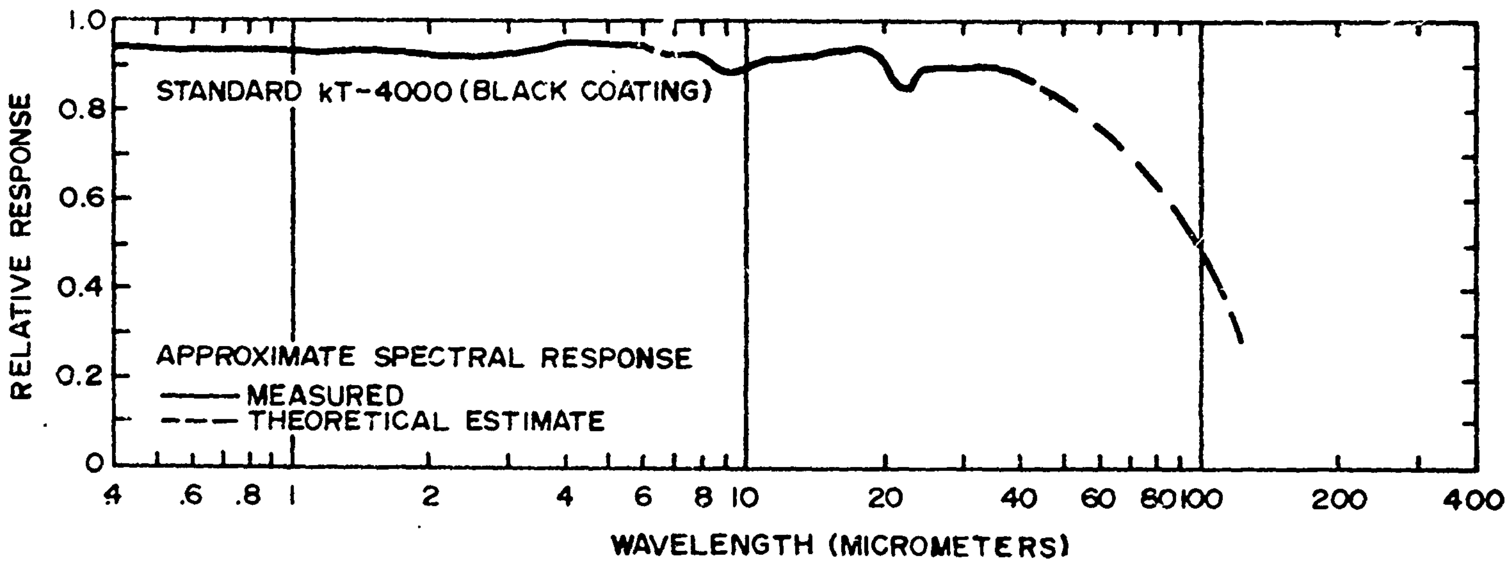


FIGURE 2. SPECTRAL RESPONSE OF THE PYROELECTRIC DETECTOR



detectors. The detector response is relatively flat in the 3.0-5.0 micrometer region, so the total radiometer response (filter + detector) will essentially be that of the filter.

2.2.3 Blackbody Calibration. The ECPR consists of a detector, separate optical chopper and associated electronics (see Table 2 for specifications). The ECPR readout is in irradiance, E_{obs}. The ECPR detector-blackbody distance should be at least ten times the blackbody aperture diameter to ensure the validity of the point source approximation. Precautions should be taken to exclude or account for background radiation, reflections, temperature variations and air currents. This is best accomplished by placing the chopper as close as possible to the blackbody so that a negligible amount of background radiation is chopped. This will also reduce fluctuation of the readings due to vibration and air currents induced by the chopper onto the detector. The effect of the chopper air current on the blackbody is negligible.

2.2.3.1 The blackbody is adjusted to 1000 degrees Celsius (1273 Kelvin) with an aperture area of 5.06 square centimeters. Temperatures should be gradually brought up in at least two stages allowing not less than 90 minutes for equilibration.

2.2.3.2 The ECPR detector is placed on the optical rail with the detector 30 centimeters away from the blackbody aperture, (See Figure 3), and with the special baffle in place in front of the blackbody aperture. (See Figure 4).

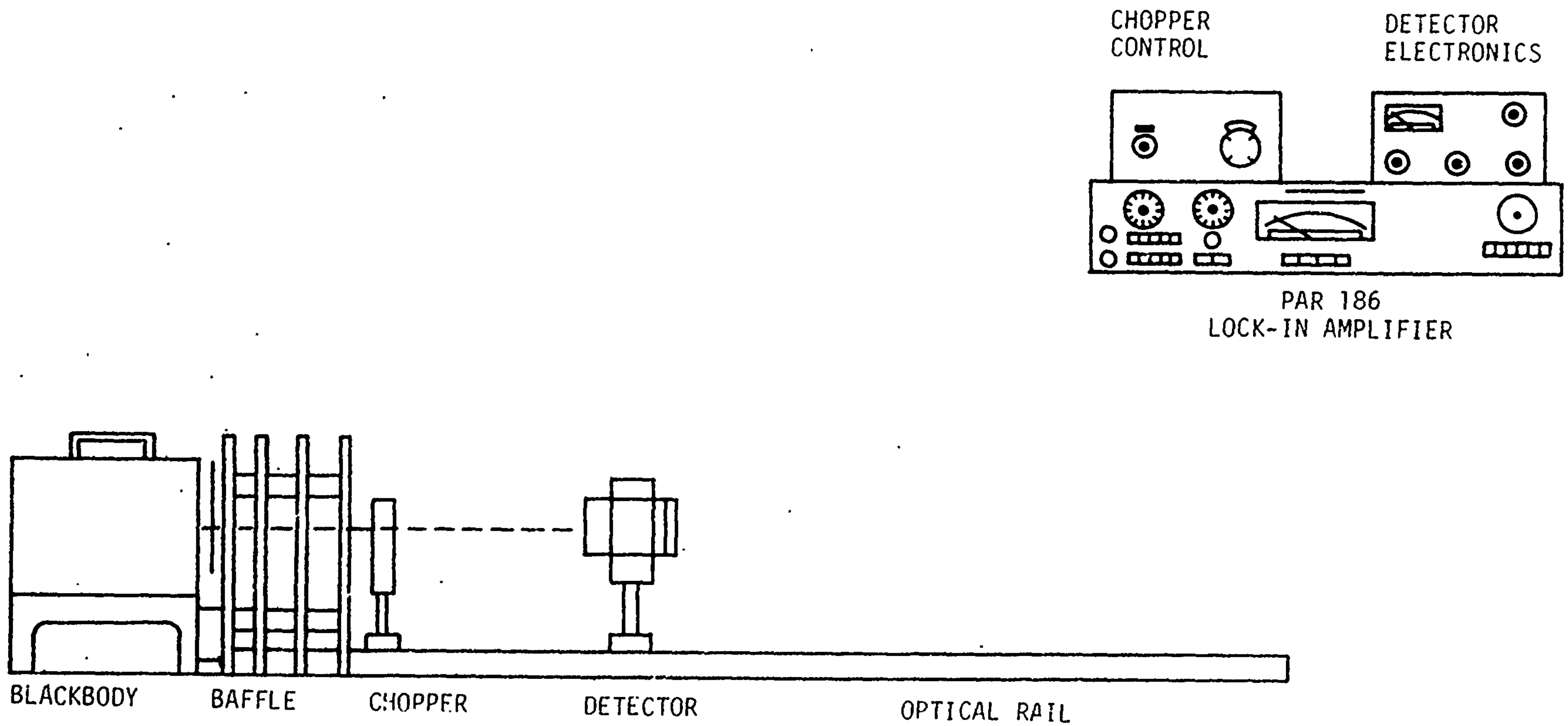
2.2.3.3 Set the ECPR chopper frequency at 15Hz.

2.2.3.4 Set the null and readout range switches.

2.2.3.5 Set the lock-in amplifier controls as follows:

Input Low Pass	1kHz
Input	A
Output Zero Offset	Off
Dynamic Reserve	30K
Mode	f

FIGURE 3. ARRANGEMENT FOR CALIBRATION OF THE BLACKBODY WITH THE ECPR



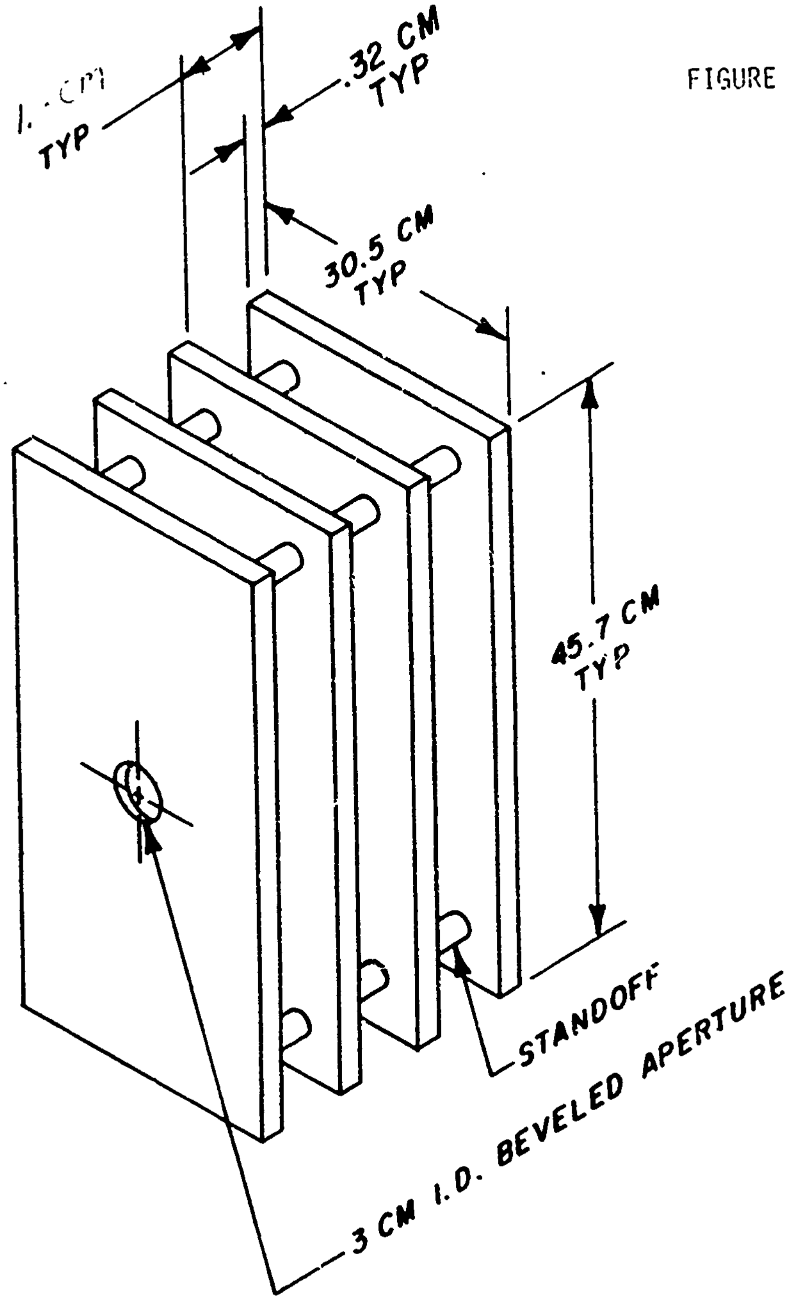


FIGURE 4. BLACKBODY BAFFLE

2.2.3.6 Set the phase control on the lock-in amplifier by setting the null controls on the readout to result in 9mW DVM indication.

2.2.3.7 Set the range switch to 20mV and adjust the phase controls for a null indication.

2.2.3.8 Switch the quadrant either up or down 90 degrees.

2.2.3.9 Record these settings, which should not change with time.

2.2.3.10 The sensitivity control should be set so as to allow a null resolution consistent with the desired accuracy. If the power to be measured is quite uncertain, it may be convenient to start with a high gain and short time constant combination and then increase the resolution after an approximate null has been attained.

2.2.3.11 With the blackbody blocked, set the null range switch to 0.1mW and the null control for zero power indication. Check to see that the null offset voltage indicated on the lock-in amplifier is approximately 15μV.

2.2.3.12 Remove the protective detector cover, and adjust the readout null control for a minimum reading on the lock-in amplifier.

2.2.3.13 Record the power reading.

2.2.3.14 Repeat the measurement at distances of 40, 50, 60, 70, 80, 90 and 100 centimeters.

2.2.3.15 When the series of measurements is complete, replace the detector cover. The blackbody should be allowed to cool down gradually. The fan should not be turned off unless the blackbody temperature is less than $100^{o}C$.

2.2.3.16 E_{band} can be calculated by the following equation:

$$E_{band} = \frac{A\, L_{band}}{R^2} \qquad \text{eqn (1)}$$

where: L_{band} is the in-band radiance at 1273K
R is distance in cm and
A is the aperture area in cm^2.

2.2.3.17 In order to compare the calculated E_{band} and measured E_{obs}, it is necessary to divide E_{obs} by $\bar{\tau}$, the average 3.0 to 5.0 micrometer filter transmittance, in order to obtain what the irradiance is in the band as if the filter had an in-band transmittance of 100%. The calculated E_{band} and the E_{band} obtained by dividing E_{obs} by $\bar{\tau}$ are then compared to establish the accuracy of the blackbody. The two values should agree within two percent.

2.2.3.18 Repeat the measurements for the 3.0 to 4.0 and 4.3 to 5.0 micrometer bands.

2.3 Pyroelectric Radiometers Calibration

2.3.1 General Description. The pyroelectric radiometers to be calibrated consist of a pyroelectric detector/preamplifier assembly, an optical chopper with controller, a lock-in amplifier and bandpass filters which pass infrared radiation in the 3.0 to 5.0, 3.0 to 4.0 and 4.3 to 5.0 micrometer bands. Three pyroelectric radiometer systems are seen in Figures 5-7. Figure 5 shows an overall view. Each system consists of a detector (A), chopper (B), preamp (C) and lock-in amplifier (D). Three systems are mounted on a single tripod, as shown. The chopper motor controls (E), and aligning telescope (F) can also be seen. Figure 6 is another view of that shown in Figure 5. Here, the amplifiers have been replaced with the tripod cover (A). In Figure 7 the choppers (A) and detectors (B) can be seen in a close-up view. See Appendix A for a further description of the radiometers.

FIGURE 5. VIEW OF 3 PYROELECTRIC RADIOMETER SYSTEMS

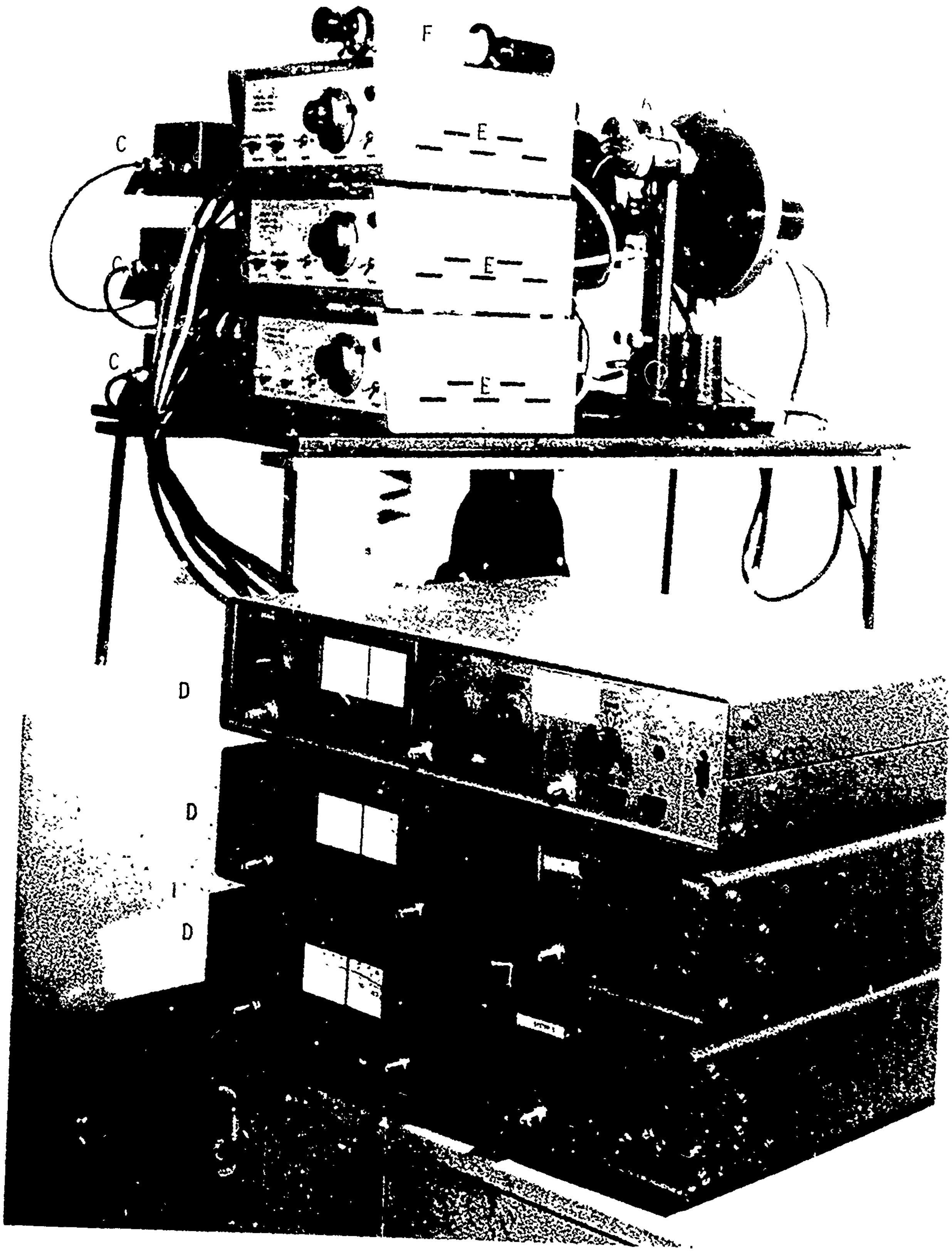


FIGURE [illegible] OF THE PYROELECTRIC [illegible] SYSTEMS

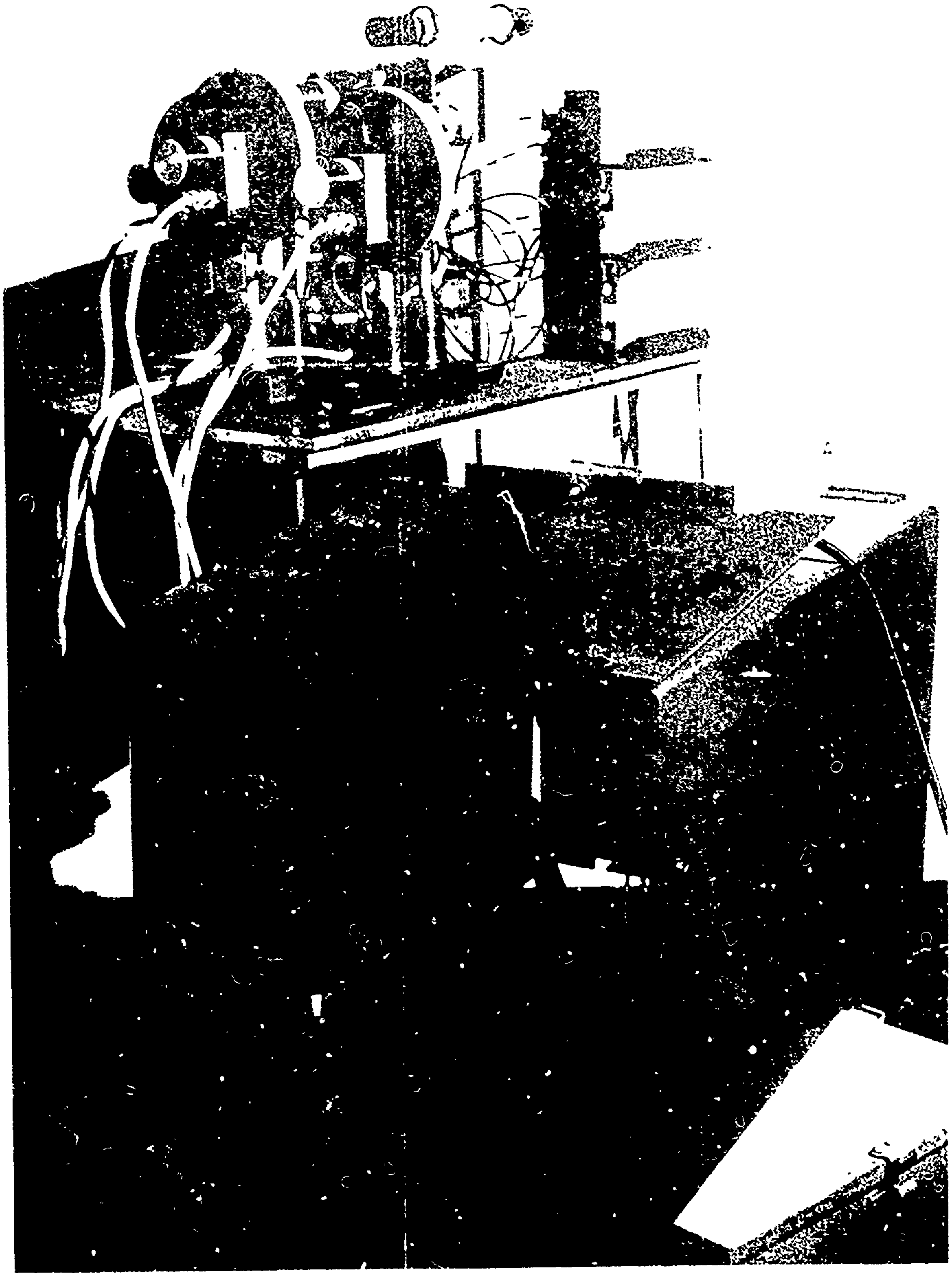
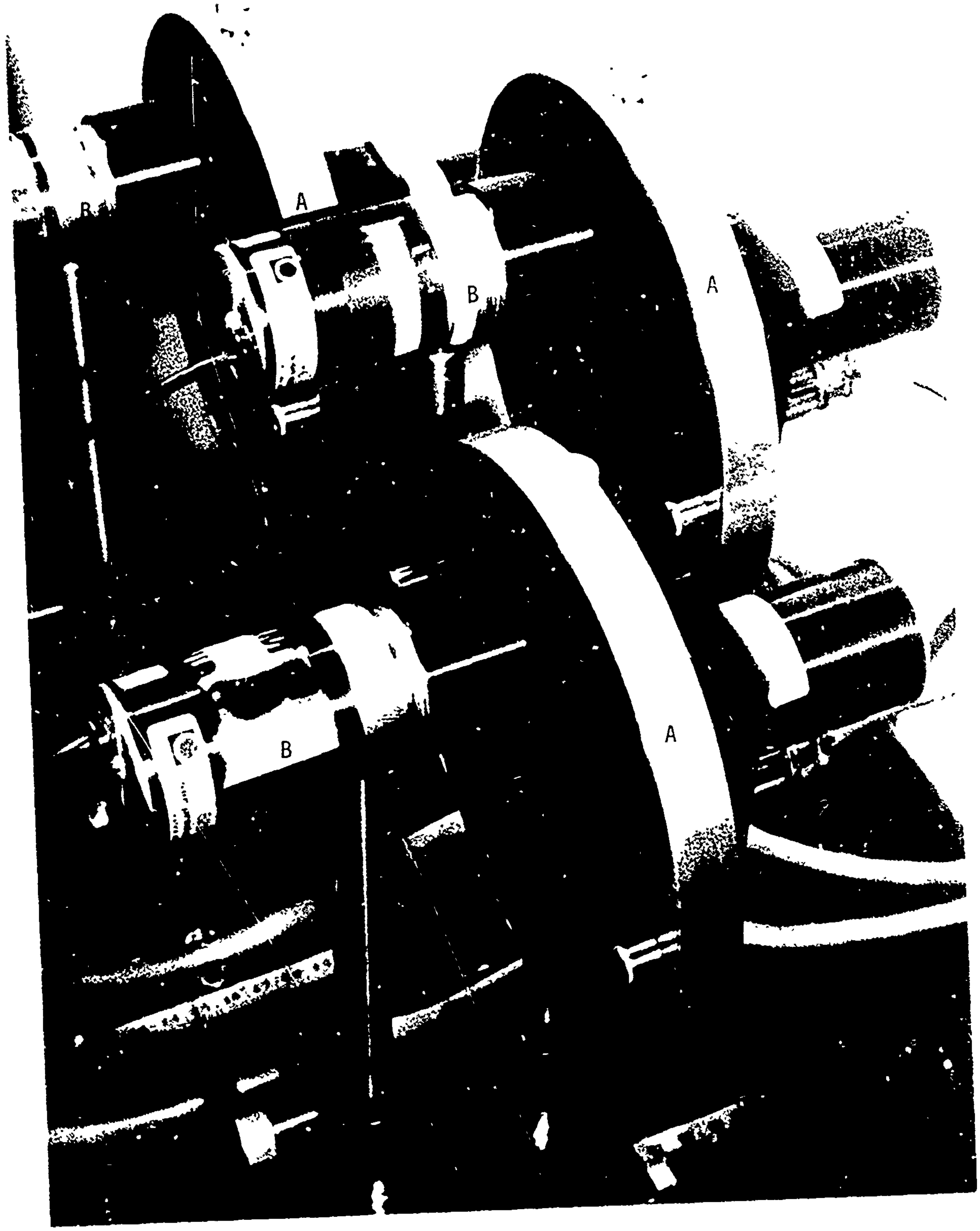


FIGURE 7. CLOSE-UP OF THE PYROELECTRIC DETECTORS AND CHOPPERS



2.3.2 Calibration with the Blackbody.

2.3.2.1 Blackbody warm-up and cool-down precautions as outlined in paragraphs 2.2.3.1 and 2.2.3.15 should be observed.

2.3.2.2 The pyroelectric radiometer must be on the optical axis of the blackbody perpendicular to the axis and the radiometer-blackbody distance should be at least ten times the blackbody aperture diameter to ensure the validity of the point source approximation. See Figure 8.

2.3.2.3 Precautions must be taken to exclude or account for background radiation and reflections.

2.3.2.4 Adjust the blackbody to 1000 degrees Celsius (1273 Kelvin).

2.3.2.5 The optical chopper and the lock-in amplifier are turned on and the lock-in amplifier is then synchronized to the optical chopper frequency of 360Hz.

2.3.2.6 The pyroelectric radiometer is positioned with the optical chopper in place between source and detector at 30 centimeters from the blackbody aperture.

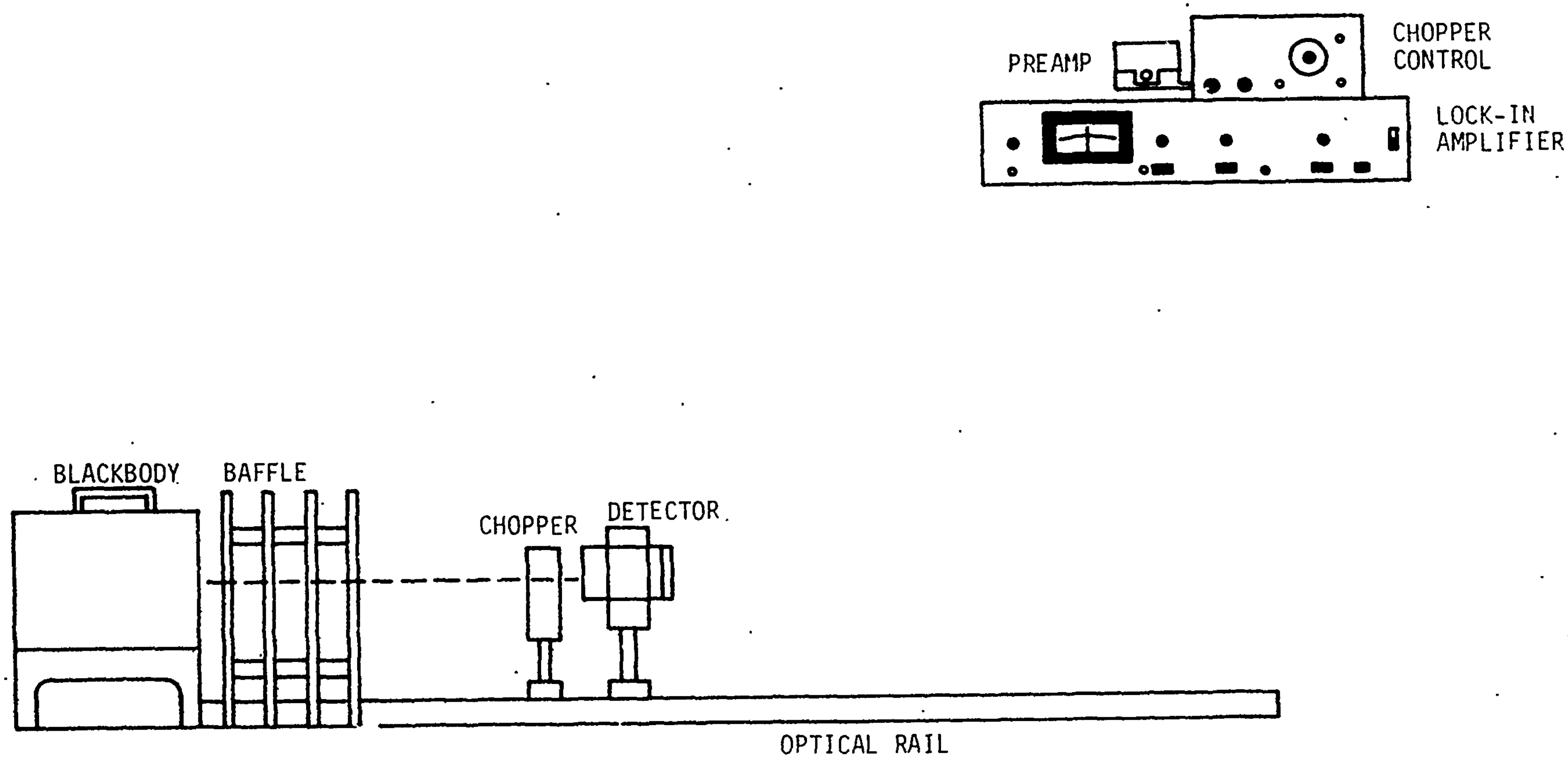
2.3.2.7 The lock-in amplifier is adjusted for sensitivity and synchronization of the optical chopper. To adjust the lock-in amplifier for proper rise-time, sensitivity and synchronization the following steps should be followed before a calibration measurement is attempted:

(a) Set reference mode switch to position f.

(b) Connect the reference synchronization from chopper control to reference input and wait until the Ref. Unlock light goes out.

(c) Connect the signal from the radiometer pre-amp to signal in and set sensitivity switch to 100mv.

FIGURE 8. CALIBRATION SET-UP FOR PYROELECTRIC RADIOMETER SYSTEM



(d) Set the zero offset to off and the post filter to off and the time constant to the 3ms position.

(e) Set the phase quadrant either up or down and adjust the phase reference control to peak output. Record the quadrant and phase setting for these should not change from calibration to calibration.

2.3.2.8 The pyroelectric radiometer and optical chopper are subsequently moved on the optical rail in steps of 10cm from 30cm through 150cm and the voltage readings taken and recorded at each position.

2.3.2.9 The irradiance as if the in-band filter transmittance were 100% is calculated by the equation

$$E_{band} = \frac{A\ L_{band}}{R^2}$$

where, L_{band} is the band radiance of the blackbody at 1273K

A is the blackbody aperture area

R is the distance in centimeters for each measurement position

2.3.2.10 A plot of voltage versus irradiance is made from each distance that was recorded and a curve is drawn through the points. This results in a calibration curve for the pyroelectric radiometer system measuring infrared radiation in the spectral region determined by the band filter that is in front of the pyroelectric detector. (See Figure 9) NOTE: If, for any reason, the pyroelectric radiometer system has changed its sensitivity (such that a spot check shows a deviation from the last calibration curve) a complete recalibration should be done.

FIGURE 9. CALIBRATION CURVES

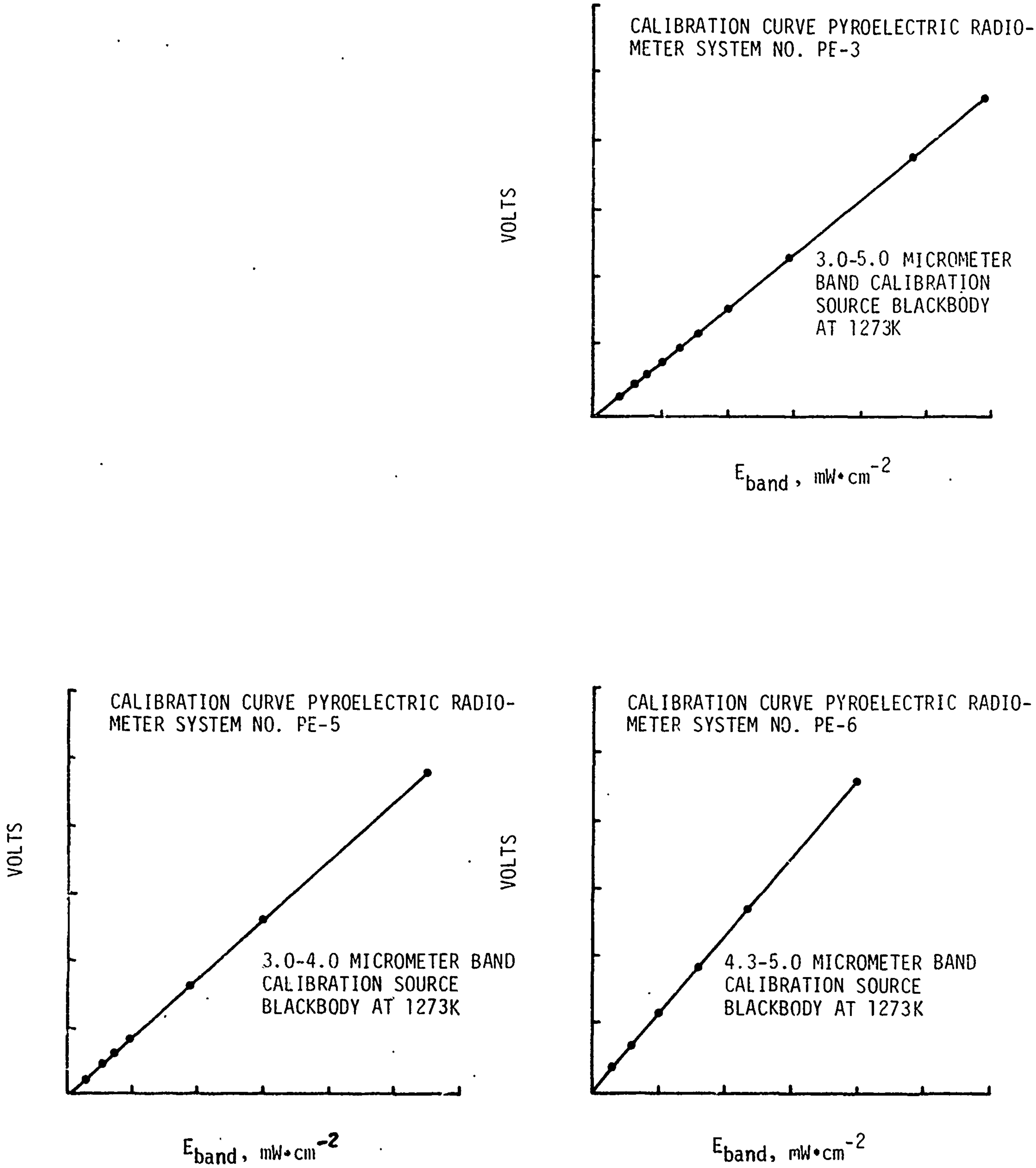


TABLE 1
CALIBRATION TIMETABLE

ACTION	TIME
1. Electrical calibration of ECPR at a qualified calibration facility	6 months or whenever a problem is encountered
2. Electrical calibration of precision voltmeters, power supplies	Varies from 3 to 12 months, depending on the particular piece of equipment
3. Calibration of Blackbody against ECPR	3 months or whenever a problem is suspected
4. Spectral measurement of infrared band filters	12 months or whenever a problem is suspected
5. Spot check of pyroelectric radiometer calibrations	Before test series and whenever a problem is suspected
6. Complete calibration of pyroelectric radiometers against blackbody	3 months or whenever a problem is suspected

TABLE 2

SPECIFICATIONS FOR ELECTRICALLY CALIBRATED PYROELECTRIC RADIOMETER*

Detector Area	$0.5 cm^2$ ($\pm$0.2%)
Maximum Irradiance	$0.2 W/cm^2$
Uniformity Across Active Area	$\pm$2% (3mm spot size)
Usable Spectral Range	Vis to far IR
Chopping Rate	15Hz
Electrical Substitution Accuracy	$\pm$0.1% of reading $\pm$0.04% of full scale (10mW scale)
Scale Ratio Accuracy	$\pm$0.1% relative to 10mW scale
Uncertainty in Optical-Electrical Equivalence	1%
Readout Resolution	0.01% of full scale
Temperature Range	15°C to 35°C for stated accuracy
	0°C to 55°C, Operating -25°C to 75°C, Storage
Response Time (Power Computation)	4.5 seconds to 99% of any step change
Noise Equivalent Power	1 X 10^{-7} with 3 second lock-in time constant

*Taken from reference 4

REFERENCES

1. (UNCLASSIFIED) Nicodemus, F.E., Self-Study Manual on Optical Radiation Measurements, NBS Technical Note 910, National Bureau of Standards, Washington, DC (March 1976)

2. (UNCLASSIFIED) Hammond, H.K., III, and Mason, H.L., Precision Measurement and Calibration, NBS Special Publication 300, Volume 7, National Bureau of Standards, Washington, DC (November 1971)

3. (UNCLASSIFIED) Hamilton, C.A., Day, G.W., and Phelan, R.J., Jr., An Electrically Calibrated Pyroelectric Radiometer System, NBS Technical Note 678, National Bureau of Standards, Washington, DC (March 1976)

4. (UNCLASSIFIED) Rs-3940 Electrically Calibrated Pyroelectric Radiometer, Operating Instructions, IS-394-05A, Laser Precision Corporation, Utica, NY (March 1977)

5. (UNCLASSIFIED) Model 186A Synchro-Het® Lock-In Amplifier, Operating and Service Manual, Princeton Applied Research, Princeton, NJ (1976)

APPENDIX A

Details of Pyroelectric Radiometers

Six main criteria were formulated for the selection of a set of radiometers:

a. Linear output-to-input characteristics for the range of irradiances expected from current and projected future infrared decoy flares, when burned in either static or airstream conditions in the NWSC Crane testing tunnel (30m maximum flare-to-detector distance).

b. System rise time of better than 5 milliseconds.

c. Ability to properly measure the time-intensity history of a burning flare.

d. Commercial availability of the complete system so that in-house modification of electronics and/or optics is not required. There is the added advantage that the manufacturer will be much more willing to repair unmodified systems when the need arises.

e. Ambient temperature operation (no liquid nitrogen cooling necessary, for example)

f. Reasonably flat spectral response from the visible to mid-infrared.

Table A-1 is a list of the components for a complete system, as purchased from Laser Precision Corporation, Utica, New York. The systems were mounted, three at a time, on a tripod-mounted baseplate. See Figures 5-7 and accompanying description in the text. Commercially available optical rails and other optical components (Figure 7) were used on the baseplate. The optical rails were mounted so that the outer two could be boresighted to the middle one, for whatever distance was necessary.

Figure A-1 shows the equivalent circuit, while Figure A-2 indicates some of the operating characteristics. Both of these were taken from reference A-1. The pyroelectric detector is an AC device, so it requires a chopper. For more details of the theory of operation, refer to reference A-2. In order to obtain a system response of faster than 5 milliseconds, it is necessary to select the correct feedback module (see Figure A-1 and Table A-1) and the correct chopping speed. Figure A-2 (a) shows the detector frequency response. The drop in responsivity begins near 300Hz. The amplifier frequency response is determined from Figure A-2 (b). By a selection of different feedback modules (change in R_f) one can increase the frequency response at a loss in sensitivity. For the present application, the 10^9 ohm module is usually chosen. With the above constraints, the chopper frequency is set at 360Hz, using the medium frequency chopper blade (Table A-1). The total arrangement is such that microphonics levels are acceptable. Other characteristics are shown in Figure A-2 (c) and (d).

Rise time was verified by measuring the response of the pyroelectric system to an approximate square wave optical input. This response, displayed on a fast oscilloscope, was compared to that of a very fast rise silicon detector amplified by and displayed on the oscilloscope. The difference in waveforms was negligible when the rise time of the waveform was adjusted to be 3msec or greater.

As a further check on the pyroelectric radiometers, flares were burned in the NAVWPNSUPPCEN Crane tunnel. The set of pyroelectric radiometers, mounted with infrared bandpass filters (Figure 1), were mounted in the tunnel, side-by-side with currently used PbS and PbSe radiometers.

The outputs were placed on the same oscillograph paper, all to the same time base. The data were then reduced using the calibration curves, such as in Figure 9. Figure A-3, a comparison of the PbSe to a pyroelectric system, is typical and shows that the time-intensity curves have similar shapes. The two curves are directly comparable--that is, they are drawn to the same time scale and to the same intensity scale after their respective calibration curves have been applied.

FIGURE A-1. EQUIVALENT CIRCUIT FOR PYROELECTRIC DETECTOR-PREAMP COMBINATION (TAKEN FROM REF A-1)

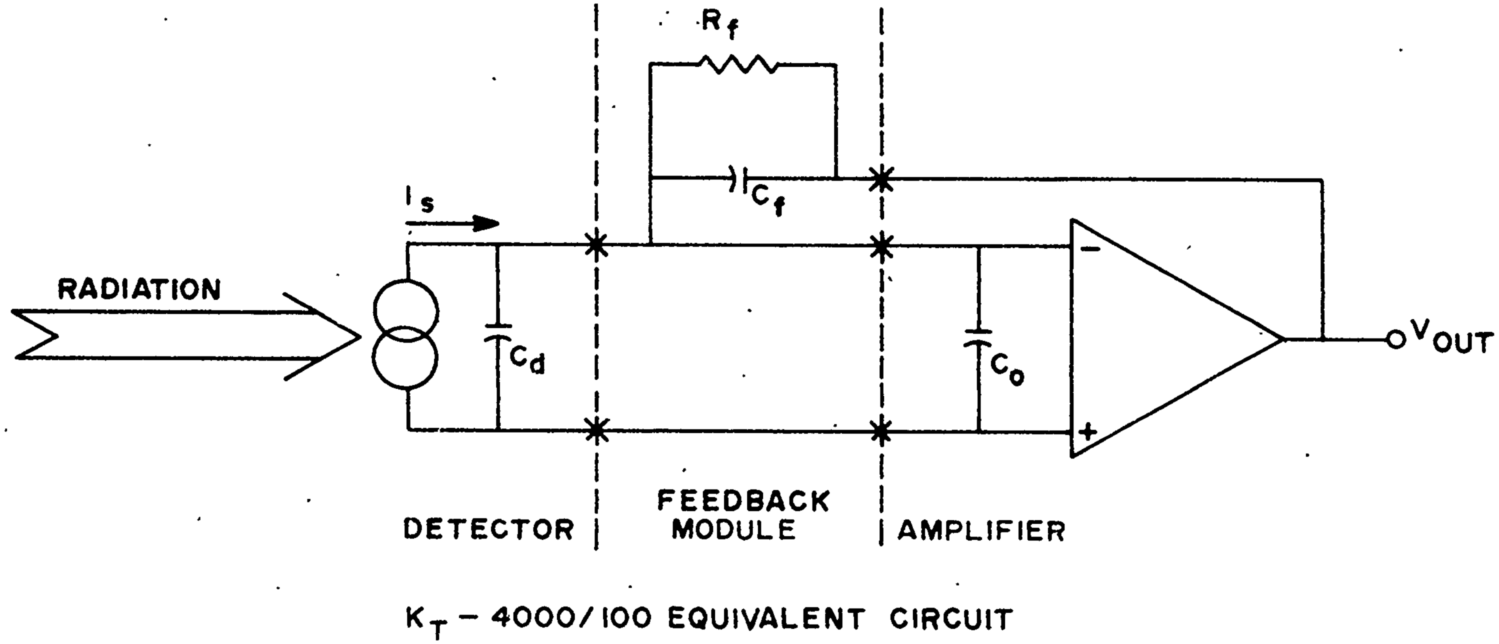


FIGURE A-2. OPERATING CHARACTERISTICS OF PYROELECTRIC DETECTORS AND PREAMPS (TAKEN FROM REF A-1)

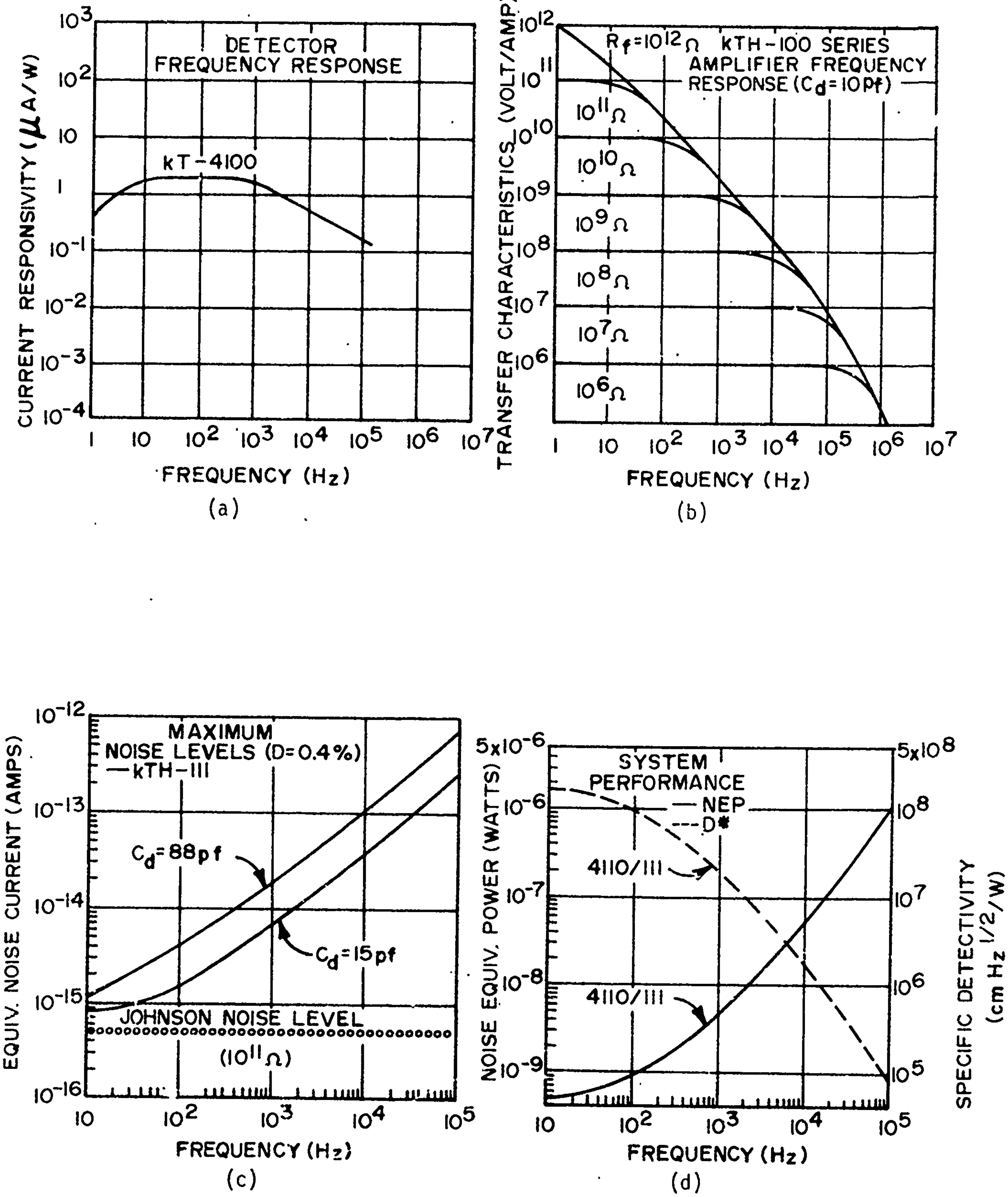
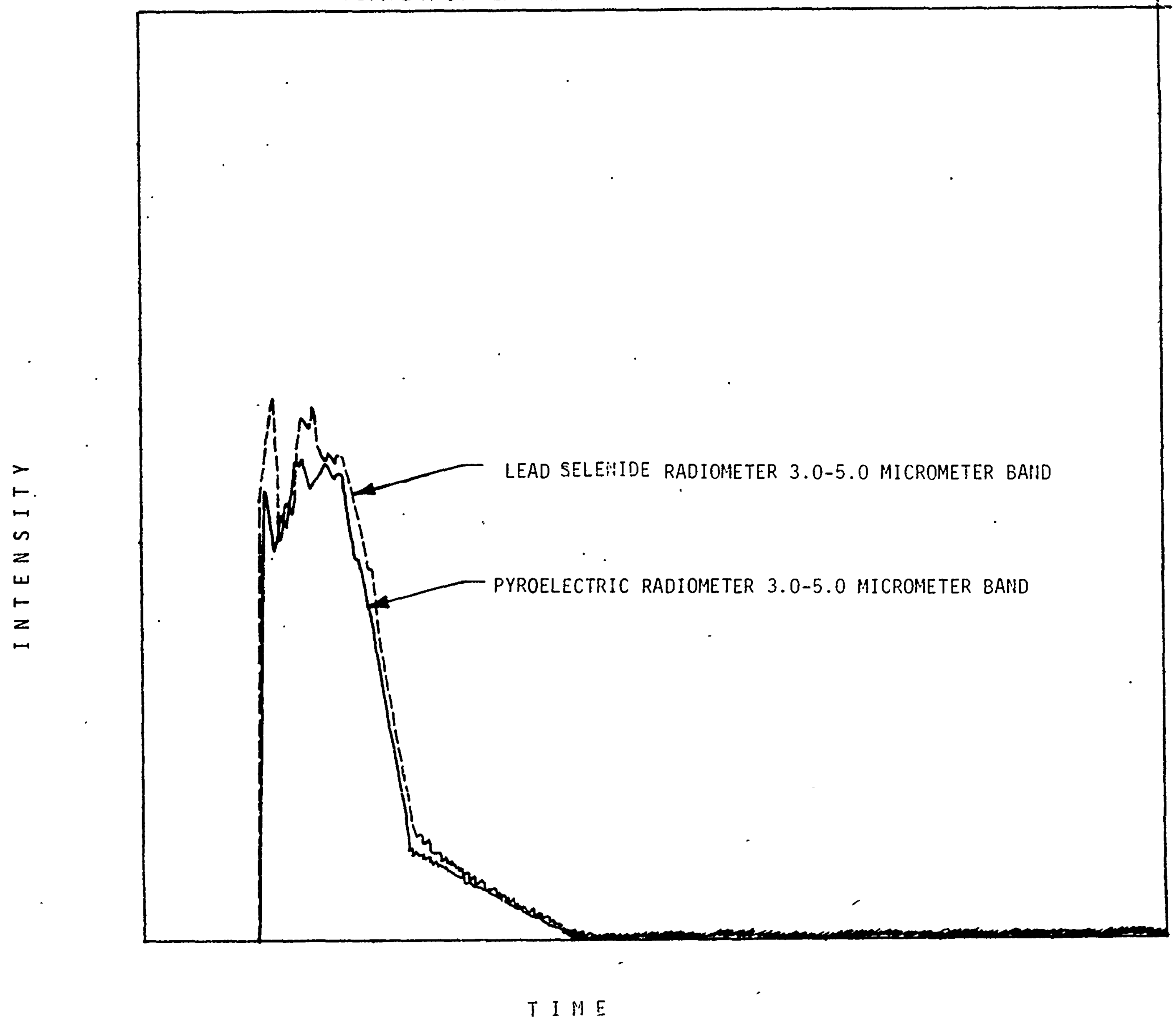


FIGURE A-3. EXAMPLE OF FLARE TIME-INTENSITY PLOT



System linearity is shown in Figure 9.

The spectral response of the detectors is shown in Figure 2, while the filter transmittances are shown in Figure 1. It can be seen that for the 3.0-5.0 micrometer region, the total radiometer spectral response will essentially be that of the filters.

Field of view measurements were taken of the radiometer system in order to insure that the radiometer views the entire flare plume. In all field of view measurements (and in all flare measurements) the detector was placed on the optical rail so that it was as close as possible to the chopper without actually touching it. See Figure 7. The closer the detector is to the chopper, the larger the field of view.

The measurements were taken in the laboratory on a small scale, but on a precisely measured basis, and verified in the tunnel at full scale. Figure A-4 shows a view from the 15m position as seen by a radiometer (the tripod-mounted instrument to the right should be ignored). The heavy black lines accentuate the end of the tunnel, opening into the burning chamber. The flare is burnt at "A."

The laboratory measurements were accomplished as follows: The pyroelectric detector and chopper are placed on an optical rail with the detector 20cm away from a 0.3cm diameter point source.

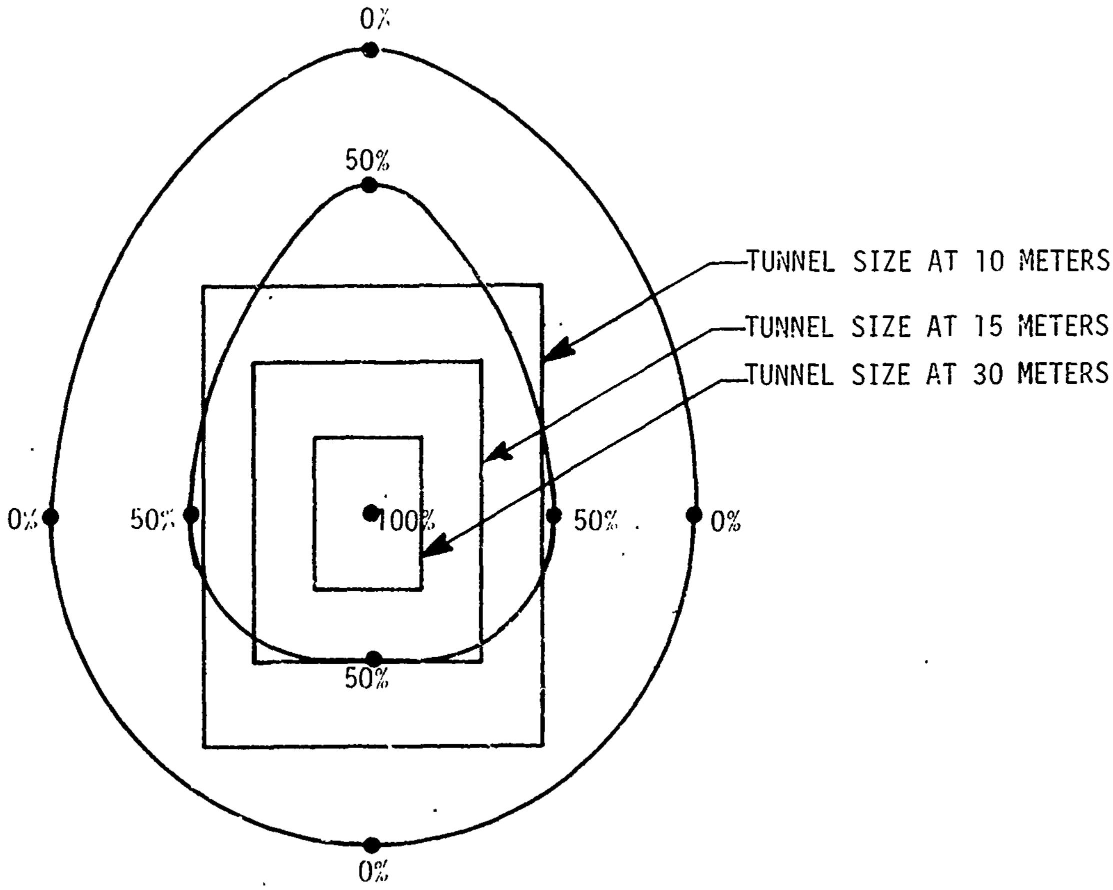
The point source is mounted on a second horizontal optical rail which is perpendicular to the first rail. The point source is then moved in 0.5cm increments and the resulting detector outputs recorded. A plot then can be made of the detector's horizontal field of view. After a change of the setup, the experiment is repeated with the point source moved in the vertical direction.

The horizontal and vertical data are combined to produce a field of view contour plot, as seen in Figure A-5, which has been normalized to 100%.

FIGURE A-4. VIE!' OF TUNNEL AT 15m DISTANCE FROM FLARE POSITION (AT "A")

FIGURE A-5. PYROELECTRIC DETECTOR FIELD OF VIEW

DETECTOR CONTOUR PLOT (OVALS) IS OVERLAID ON THE APPARENT SIZE OF THE EDGES OF THE TUNNEL AT DIFFERENT DISTANCES.



Selected points from the laboratory data were verified in the tunnel using an electrically heated infrared radiant source (6.5 X 5.0cm) and a two-dimensional vertical grid with intersection points 15cm apart.

In Figure A-5, superimposed on the contour plots are the outlines of the end of the tunnel (drawn to scale) as seen by the radiometer from distances of 10, 15, and 30m. The radiometers are oriented such that the 100% response point coincides with the center of the flare plume.

TABLE A-1

Pyroelectric Radiometer System (Laser Precision Corp., Utica, NY)

MODEL	DESCRIPTION
kT-4130	Pyroelectric detector, high sensitivity model, 3mm dia. sensor
kTM-909	10^9 ohm feedback module
kTM-910	10^{10} ohm feedback module
kTM-911	10^{11} ohm feedback module
kTH-111	Low noise detector preamplifier
CTX-534	Variable speed optical chopper
CTD-503	Low frequency chopper blade, 5 to 333Hz
CTD-504	Medium frequency chopper blade, 15 to 1000Hz
CTD-505	High frequency chopper blade, 60 to 4000Hz
kTS-215	±15VDC power supply for kTH-111 preamp.
PAR 5101	Princeton Applied Research lock-in voltmeter

REFERENCES

A-1. (UNCLASSIFIED) kT-4000/100 Radiometric Detection Systems, Bulletin PS-40-05, Laser Precision Corporation, Utica, NY (April 1975)

A-2. (UNCLASSIFIED) Doyle, W. M., "Guide to Pyroelectric Detection," in Electro-Optical Systems Design, p. 12, (November 1978)

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